Low-Emissivity Materials for Building Applications: A State-of-the-Art Review and Future Research Perspectives

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Abstract

Low-emissivity (low-e) materials can be used in order to reduce energy usage in both opaque and transparent areas of a building. The main focus for low-e materials is to reduce the heat transfer through thermal radiation. Furthermore, low-e materials will also influence on the daylight and total solar radiation energy throughput in windows, the latter one often characterized as the solar heat gain coefficient (SHGC). This work reviews low-e materials and products found on the market, and their possible implementations and benefits when used in buildings. The SHGC is often left out by many countries in energy labellings of windows. With opaque materials, research is still ongoing to correctly calculate the effect with regard to thermal performance when applied in buildings. Future research perspectives on where low-e technologies may develop are explored. To the authors' knowledge, there seems to be little available literature on how ageing affects low-e materials and products. As this is of large significance when calculating energy usage over the lifetime of a building, ageing effects of low-e materials should be addressed by manufacturers and the scientific community.

Keywords: Low-emissivity; Low-e; Building; Energy; State-of-the-art; Review.

Contents

1 Introduction

Energy usage in buildings represents about 40 % of the total energy usage in Europe. The European Union has set a goal to reduce the energy usage in buildings by 20% by 2020 and 50% by 2050, compared to values from 1995 (European Union [15]). A large part of the energy usage is directly related to heating and cooling demands for buildings. Transparent surfaces, e.g. windows and skylight glazing, contributes to a substantial part of this energy loss. In areas with hot climates, an increase in cooling demands, i.e. increased energy usage, due to overheating caused by high radiation throughput is a common problem. A reduction in the radiative heat transfer may lower cooling needs in the summer and may also be beneficial with respect to lower heating needs in the winter assuming that you can keep the heat from radiating to the outside. To achieve such building envelopes, with a passive reduction in energy usage, low-emissivity (low-e) materials are of large interest. However, an important factor to consider with low-e materials are geographical climate conditions. The possible effects gained are highly different between cold climate regions, hot climate regions and regions with both warm summers and cold winters (Shi and Zhang [69]).

Low-e materials and coatings can be applied in both the opaque and transparent parts of a building envelope. For transparent parts, i.e. glazing, low-e solutions consist of coatings which are added during or after the production of the glass by the manufacturers themselves, or do-it-yourself films that can be applied on the inner side of glazing even after they have been installed. It is important to consider the net energy consumption for windows as they include both transmission losses and solar energy gains (Fang et al. [17], Grynning et al. [21], Jelle [38]).

Opaque parts of a building envelope use low-emissivity solutions that consist of various low-e foil products or spray coatings. A review performed by Medina [49] showed that applying radiant barriers (i.e. low-e foils) and spray coatings can significantly reduce heat transfer across attic spaces and thereby lead to a reduction in space cooling loads.

To the authors knowledge there seems to be little available literature on how ageing affects the performance of low-e materials under building related conditions. This may be a field of interest for future research, as it is important to know both with regard to energy performance over a components lifetime and the need to plan for replacement of aged parts.

The objective of this study is twofold, i.e. (a) to present an overview of different low-e coating and material producers and products, and to evaluate the effect and durability of these products, and furthermore (b) to explore possible future research perspectives. In addition, it is of interest to see how low-e solutions are tested with respects to lifetime performance in building applications. These investigations may help for guidelines for a new testing scheme and point to future research perspectives. This work presents many tables with a lot of information, e.g. manufacturers, product names and various properties, both in the main text and in the appendices. Some of these values are crucial to the performance of low-e coatings and materials. The tables should provide the readers with valuable information regarding low-e solutions. Unfortunately, it is currently hard to obtain all the desired information from every manufacturer. In general, many of the desired property values are not available on the manufacturer's websites or other open information channels, which is hence seen as open spaces in the various tables. Hopefully, our addressing of these facts could act as an incentive for the manufacturers to state all the important properties of their products at their websites or other open information channels, and also as an incentive and reminder for consumers and users to demand these values from the manufacturers.

2 Low-emissivity concepts

2.1 General

2.1.1 Solar energy

The largest parts of energy from the sun can be found in the visible (380-780 nm) and near infrared spectrum (780-3000 nm) (Fig.1). Solar radiation onto a surface will be reflected, transmitted and absorbed. The division of solar radiation onto a surface is dependent on the wavelength (λ), incident angle and the materials optical properties. The sum of the fractions of a materials transmittance (T), absorbance (A) and reflection (R) is given by (Jelle [38]):

$$T(\lambda) + A(\lambda) + R(\lambda) = 1 \ (100\ \%) \tag{1}$$

The solar energy which is absorbed in the material is equal to the energy emitted, i.e.:

$$A(\lambda) = E(\lambda) \tag{2}$$

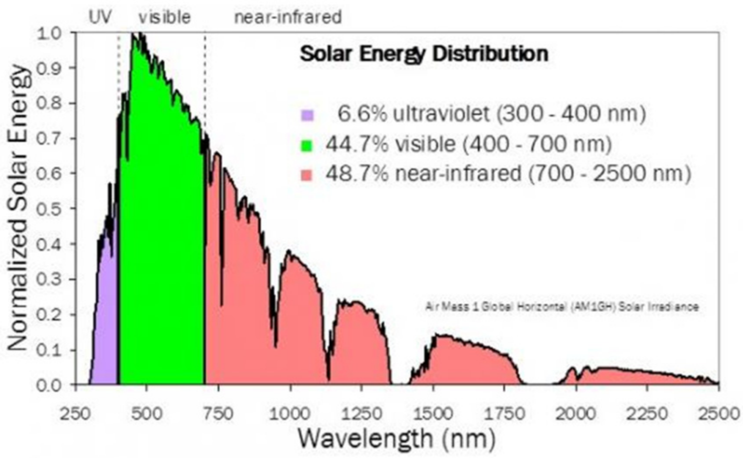

Figure 1 Solar energy distribution (Heat island group, Berkeley National Research Laboratory [25]).

However, for an opaque material there is no transmittance ($T(\lambda) = 0$). Hence, Eq.1 may be written as:

$$A(\lambda) + R(\lambda) = 1 \ (100\ \%) \tag{3}$$

This gives an emissivity of

$$E(\lambda) = 1 - R(\lambda) \tag{4}$$

for opaque materials (Wu and Yu [75]).

Unwanted solar radiation is a large contributor towards increased energy usage in buildings. Controlling the radiative heat given off by the sun and utilizing the solar energy when needed is the key to attain more energy-efficient buildings. The idea of low-e materials is to reduce the radiative heat conduction, either in to, or out from a building. Near-infrared radiation is reflected by the material, and long-wave infrared radiation given off at room temperature from materials inside is reflected back into the room maintaining a higher indoor temperature. Transparent materials, e.g. glazing, will allow visible parts of the solar spectrum to pass through. The different solar radiation glazing factors are described in the comprehensive study by Jelle [38], where e.g. T_{uv}, T_{vis} and T_{sol} denote (integrated values over specific parts of the solar spectrum) the ultraviolet solar transmittance, the visible solar transmittance, and the solar transmittance, respectively. Furthermore, the solar factor (SF) represents the total solar energy transmittance which is also called g-value and solar heat gain coefficient (SHGC). The climate in which the materials are intended must therefore be considered, as areas dominated heating loads or cooling loads will utilize solar energy gain in different ways. Simply installing a low-e material without sufficient planning may remove all the possible positive effects, e.g. the energy saved during summer may be neutralized by increased energy use in the winter. Because of this difference between transparent and opaque materials, separate explanations for transparent and opaque materials will be given in the following.

2.1.2 Angle dependency

A surface whose emittance is the same regardless of direction is called a diffuse emitter. However, no real surface can be a diffuse emitter and emittance will vary with the incident angle. Figure 2 shows the directional variation of surface emittances for several nonmetals and metals (Modest [54]). It is clear that metals show lower emittance values at most angles compared to traditional construction materials such as e.g. wood, glass and clay. Hence, these materials are often used for low-emittance solutions.

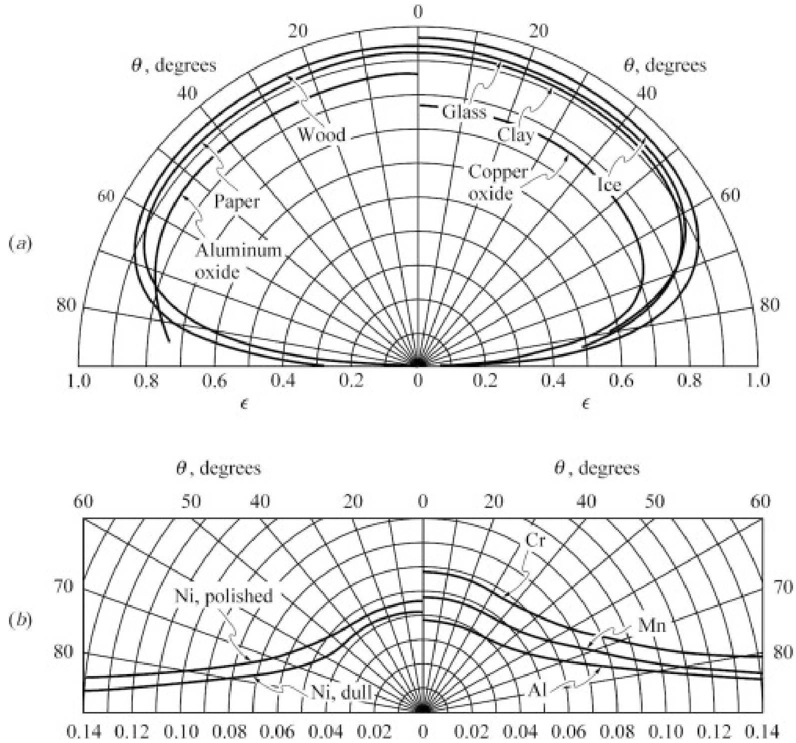

Figure 2 Directional variation of surface emittances (a) for several nonmetals and (b) for several metals (Modest [54]), also depicting the normally much lower emittance (on the x-axis scales) for the latter ones.

2.2 Transparent materials

2.2.1 Transparent materials in general

When low-e materials are applied to transparent areas of a building envelope there are some different requirements which need to be considered versus low-e materials that are applied to opaque areas. Glazed areas are in many cases added to be architecturally pleasing and to allow visible light inside. A low-e coating for glazing should show spectral selectivity, i.e. have a high transmittance in the visible range of the spectrum to allow visible light inside, and at the same time provide high reflectance in the near infrared part of the spectrum (Park et al. [59]). Note that because of the extra energy provided by visible light transmitting through the window, the solar heat gain will be larger through transparent areas of a facade. Controlling the solar gain so that unwanted overheating does not occur due to excessive heat through glazed parts of a facade, or so that desired heat stays inside the building during cold seasons is a challenge for optimizing transparent areas.

Desirable characteristics for a low-e coating for glazing as mentioned by Leftheriotis and Yianoulis [45] are:

1. Low-e coatings must exhibit high transmission in the visible part of the spectrum.

2. The emittance must be low in order to prevent the heat from the interior to be transmitted outside.

3. The coating must have long-term stability under solar irradiation. Coatings on glazing are exposed to sunlight for large periods of time during their useful lifetime. However, no form of long term degradation should be present.

Standard clear glass has an emissivity value of about 0.84 for the long-wave part of the spectrum, i.e. 84 % of the solar energy is absorbed and emitted from the glass (Karlsson and Roos [43]). Low-e coatings greatly reduce the emissivity of a glass pane. In general, two different methods are used when coating the glass surfaces, and each method has different advantages and drawbacks, as well as various results on the emissivity value. In the following, the different methods of applying low-e coating to glazing will be explained.

2.2.2 Hard coatings

Hard coating is the result of applying a low-e coating during the production of the glass. These coatings are often also referred to as pyrolytic coatings or on-line coatings. The on-line coating process applies doped metal oxides to the glass surface while it is still heated. The common method used to apply a hard coating is by chemical vapour deposition (CVD).

Fluorine-doped tin oxide is a largely used option for low-e hard coatings. Tin oxide can be applied by atmospheric pressure CVD and has a high transparency for visible light, high reflectivity for infrared light, high mechanical hardness and good environmental stability (van Mol et al. [56]).

A hard coat becomes a part of the glass, i.e. the glass can be shaped, hardened, etc. after manufacture. Hard coatings have higher stability towards chemical and mechanical wearing than soft coatings. Thus, making it possible to use hard coated glass on exposed surfaces, e.g. single pane windows and anti-condensation glass. As these coatings can be used on exposed surfaces, it is of interest to know how they react to climate stresses with respect to their aged performance.

2.2.3 Soft coatings

Soft coatings, also referred to as metal-based multilayer coatings, are applied to the glass after it has hardened. The process usually involves high-rate magnetron sputtering with layers of at least one conductive metal layer with a thickness of about 10 nm. The most preferred option for the metallic layer is silver due to its good optical properties. Copper and gold can also be used, however they show unwanted short-wavelength absorption for wavelengths under 0.5 µm (Granqvist [20]). As the metallic layers, with the exception of gold, degrade by oxidation, they are added in between optically transparent dielectric layers (Mohelnikova [55]). The dielectric layers can consist of various oxides, such as zinc, tin, bismuth or titanium, with a thickness of below 40 nm. The metallic layers provide the thermal and solar reflectivity, the dielectric layers may provide antireflective functions in the visible spectrum while at the same time protecting the metallic layers from chemical and mechanical damage (Meszaros et al. [50]).

The soft-coating process has a higher cost than the hard-coating process, and the soft coatings are not as robust. Hence, soft coatings can only be applied to multi-layered windows on the surfaces facing the cavities. In general, soft coatings do provide a lower emissivity value than hard coatings, and transmit more visible light (Commercial Windows [11]).

2.2.4 Self-applicable films

Films consist mainly of several layers of metalized polymers containing an adhesive to be applied directly on the inward facing surface of a window. These are films that are possible to apply to a window even after they are installed. Current films can only be applied to the inside of the window as they are not durable enough to handle outside climate conditions.

Even though these films cost less than industry coated glass, and are a simple solution to gain low emissivity for a glass pane, they have some considerable drawbacks. Self-applicable films gives windows a slight tint, impairing visibility and transmitted light, some films cannot be removed once applied. Films may also impair with the window manufacturer's warranty as the expansion of the glass will be altered after the film is applied due to temperature differences. Note that even though the films are self-applicable, applying them incorrectly can cause air bubbles between the film and the glass, which is aesthetically displeasing and may affect the effectiveness of the film (Home renovations [26]).

2.2.5 Suspended films

Suspended films work by implementing a film or a sheet in between two glass panes in an insulating glazing unit (Fig.3). The film is not attached or applied directly to any of the glass surfaces, but forms an additional layer inside the cavity. Installing a suspended film divides the section inside the cavity. Hence, contributing to lowering the total U-value of an insulating glazing unit. As the film is very thin it does not increase the thickness of the unit, and the increased weight is minimal compared to having a third glass pane. The films are treated to withstand UV-degradation and are protected from scratching , wear and weathering by being placed inside the cavity. (Commercial Windows [10]). A double pane window with a suspended film installed is often referred to as a triple glazed suspended film.

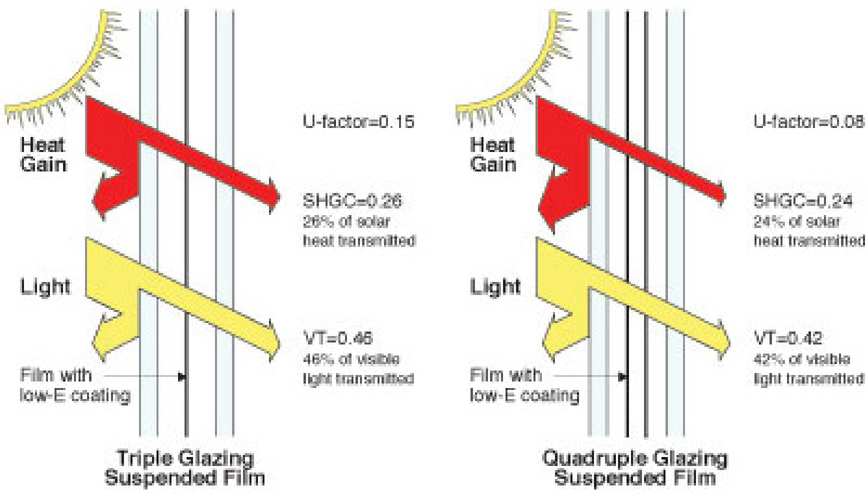

Figure 3 Illustration of suspended films in an IGU (Commercial Windows [10])

2.3 Opaque materials

2.3.1 Opaque materials in general

Adding low emissivity opaque materials to a building envelope is most beneficial in warm climate areas. Building norms in warm climates does generally not consist of adding thick layers of insulation to the building envelope and the excess heat from the sun is unwanted for larger parts of the year. A radiant barrier will provide a more effective reduction in energy usage as it will block off more solar energy and reduce indoor temperatures, i.e. reduce the need for mechanical cooling.

There are two common solutions that consist of adding low-e properties to the building envelope. One consists of adding a foil product as an insulation layer to reflect radiant heat, the other consists of adding a layer of paint with low-e properties which fulfils the same purpose. Both are explained further in the following.

2.3.2 Reflective insulation and radiant barriers

For low-e foils used as thermal insulation the terms reflective insulation and radiant barriers are commonly used. Reflective insulations is defined as a thermal insulation consisting of one or more low emittance surfaces, bounding one or more enclosed air spaces. Reflective insulation consists of layers of aluminium, paper and/or plastic to trap air and reduce convective transfer. The aluminium part provides the reflective part of the insulation with an emittance value of 0.03. When installing reflective insulation, it is important to allow a sufficient airspaces (Fig.4). If materials are in direct contact with the aluminium on both sides, it will conduct heat straight through the material (RIMA [63]). Reflective multi-foil insulation was introduced onto the building market slightly more than a decade ago. Because of its low emissivity, radiation through the material is significantly reduced, giving low-e foils a high thermal resistance. Thermal resistance values up to 5 or 6 m^2K/W has been claimed. There has however been debates, if these claims are correct (Tenpierik and Hasselaar [72]).

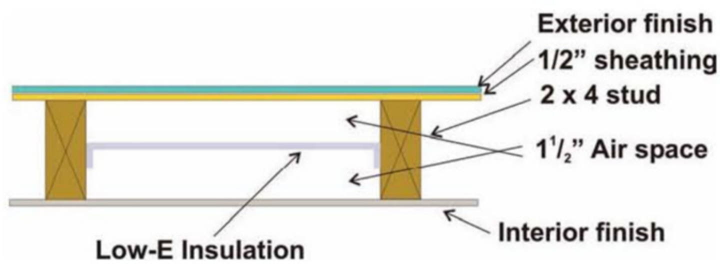

Figure 4 Illustration of installed reflective insulation with airspaces (Low-e reflective insulation [46])

Radiant barriers are mainly metalized films or aluminium foil sheets laminated to paper, polymer films, oriented strand board or plywood (Medina [49]). These foil products also works as vapour barriers. However, they can be perforated to allow vapour to pass through.

2.3.3 Spray and brush paints

Most common paints for low-e application are paints containing aluminium, silver dust, ceramic beads or sodium borosilicate microspheres (Principi and Fioretti [61]). Spray and brush paints are used to reduce the emittance of the surface they are applied to. It can either be applied to surfaces of an already existing building surface, or be applied to components before they are installed. However, it is always required that there is an airspace of minimum ≈ 4-5 cm between the painted surface and the following material.

Spray and brush paints make for easy application of a low emissivity barrier. As of today, most spray paints are categorized as interior radiation control coating systems (IRRCS), and these have to achieve an emissivity value of less than 0.25. This value is higher than for foil products, but IRCCS can be used where the cost of a foil product would be too high or the installation of a foil would be impractical (RIMA [64]).

3 State-of-the-art low-emissivity building products

3.1 General

There are a variety of products on the market that state they have low-e properties. However, an emissivity value that quantifies something as low-e is undefined. In this chapter, tables containing information about the manufacturers and their various products will be given. Note, that in this study, products that have been categorized as low-e products by the manufacturers themselves have been included in the tables.

3.2 Low-emissivity products

3.2.1 Glazing with factory applied coatings

Low-e glazing was introduced to the market in 1979, and was an improvement towards more energy-efficient glazing. Sweitzer et al. [71] concluded that low-e windows was a significant improvement, especially in cold climates. This shows that low-e windows has been of interest for well over 30 years now. Low-e windows has already been adapted as a current standard practice for most European countries when new windows are installed in buildings. Hence, there is a wide group of manufacturers that supply low-e coated windows to the market. Both soft and hard coated windows are considered as factory applied coatings, even though their area of use may vary. As there are many manufacturers of low-e glazing, it would be to extensive to include them all in this work. Hence, the manufacturers and products presented only provides examples of what can be found on the market now. Table 1 shows literature data for glazing with low-emissivity coatings.

Table 1 Literature data for manufacturers of glazing with low-e coatings.

Manufacturer	Product	ε	ε_{aged}	T_{sol} (%)	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	Standard or tool*
Guardian Climaguard	Climaguard 55/27				55	18	0.28		Window 6
	Climaguard 62/27				62	5	0.27	Soft coat	
	Climaguard 63/31				63	24	0.31		

Manufacturer	Product	ε	$ε_{aged}$	T_{sol} (%)	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	Standard or tool*
Pilkington	Climaguard 70/36				70	30	0.36		EN 410 and EN673
	Climaguard 71/38				71	24	0.39		
	Climaguard 80/70				81	41	0.70		
	K Glass	0.16			76		0.78	Hard coat	
	K Glass S				81		0.75	Soft coat	
	K Glass OW				78		0.79	Hard coat	
	Optitherm S1	0.013						Soft coat	
	Optitherm S3	0.037			80			Soft coat	
	Insulight Therm								
	Spacia			62	78		0.67		
	Anti condensation			60	70		0.71	Hard coat	
PPG Industries	Sungate 400				78	32	0.68		NFRC Methodology
	Sungate 500				76	49	0.70	Hard coat	
	Sungate 600				73	45	0.70		
	Solarban 60				72	21	0.39		
	Solarban 67				55	13	0.29		
	Solarban 70XL				64	6	0.27		
Walshglass	Evantage			41	56	19	0.53		Window 5.2
	Sunergy			40	57	31	0.50		
	EnviroShield			33	61	1	0.43		
	ComfortPlus			42	66	1	0.54		
Cardinal Glass Industries	LoE-366				65	5	0.27	Soft coat	Window 6.3
	LoE-270				70	14	0.37		
	LoE-272				72	16	0.41		
	LoE-180				79	29	0.69		
	LoE-240				40	16	0.25		
	LoE-i89								
AGC GlassEurope	Planibel G				75		0.74	Hard coat	EN410. EN673 and EN12898
	Planibel TOP				78		0.61		
	Planibel LOW-E Antifog				72	17	0.63		
Saint-Gobain Glass	SGG Planitherm Total				79	35	0.63		
	SGG Planitherm Total 1.3				77	35	0.66		

Manufacturer	Product	ε	ε_{aged}	T_{sol} (%)	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	Standard or tool*
	SGG Planitherm Ultra N				80	33	0.63		
	SGG Nano								
Clear Glass Solutions	Planibel G				74		0.71	Hard coat	
	Comfort E2				75		0.72	Hard coat	
	Sunergy clear				69		0.62	Hard coat	
	Planibel Energy N				79		0.64	Soft coat	
CSG Architectural Glass	Single Silver Low-E								
	Double Silver Low-E								
	Triple Silver Low-E								
Milgard corporate	Suncoat Low-E2				70	16	0.37-0.41		Window 5.2
	Suncoat MAX Low-E3				66	5	0.27		
Viridian	EnergyTech				73		0.61	Hard coat	
	PerformaTech E				58		0.32		
	Sunergy				68		0.59	Hard coat	
	EVantage				68		0.63	Hard coat	
	SolTech				73		0.61	Hard coat	
	SmartGlass			68	83	54	0.72	Hard coat	
	ComfortPlus				82		0.68		
Glaströsch	Silverstar zero E				80		0.60		EN 410 and EN 673
	Silverstar zero Eplus				74		0.53		

*Standards or calculation software used by manufacturers to validate given values.

3.2.2 Transparent self-applicable films

The self-applicable films are an easy and low-cost solution when compared to replacing the windows for a higher energy-efficiency. Even though the films are self-applicable, every manufacturer recommends the use of a professional installer to avoid air-bubbles and obtain the best possible visual result. In general, most of the films available have emissivity values that are far higher than the factory applied coatings. However, the fact that they can be applied to already installed windows will allow a benefit towards lower energy usage until a window with a factory applied coating can be installed. Table 2 shows literature data for low-emissivity window films.

Table 2 Literature data for manufacturers of low-e window films.

Manufacturer	Product	ε	ε_{aged}	T_{sol} (%)	T_{vis} (%)	T_{uv} (%)	SHGC	Standard or tool*
CPFilms	EnerLogic VEP35	0.07		15-19	29-33	1	0.24	NFRC
	EnerLogic VEP 70	0.09		35-46	61-70	1	0.49	

Classic window film	Solar Window film						
Saint-Gobain	SolarGard Ecolux Low-e	0.09	43	68	< 1	0.48	
	Silver AG 50	0.37	35	51	< 1	0.43	
	Silver AG 25	0.33	14	22	< 1	0.23	
Hanita Coatings	Silver 20 Low-E	0.39	12	17	1	0.20	NFRC
	Silver 35 Low-E	0.45	19	27	1	0.28	
3M	Amber 35 Low E Sun Control	0.34		31	1	0.31	

*Standards or calculation software used by manufacturers to validate given values.

3.2.3 Opaque foils

From the information found about these products, their most common use is in attics and walls in regions dominated by cooling loads. By reflecting large parts of the incoming solar heat it reduces temperature rise inside the building. Thus, reducing the required energy to keep the indoor temperature comfortable. Most of the foils have the ability to work as a combined vapour and radiant barrier, or they may be perforated to allow vapour to pass through. Reflective insulation is more effective in climates where cooling loads are dominant (Al-Hamoud [4]).

The different terms radiant barrier and reflective insulation are often used. Both have the same ability to block incoming radiation. However, a radiant barrier refers to a fairly thin product that only aims to block radiant heat. Reflective insulation is a thicker product combined with an insulating layer, e.g. fibreglass, foam or air bubbles, to achieve higher thermal resistance. Table 3 shows literature data for low-emissivity foil insulation/radiant barriers.

Table 3 Literature data for manufacturers of low-e foil insulation/radiant barriers.

Manufacturer	Product	ε	ε_{aged}	Thickness (mm)
Environmentally safe products	ESP- LOW-E	0.03		
	Econo-E	0.03		
	Attic Floor Insulation	0.03		
	LOW-E HVAC	0.03		
	SlabShield			
	LOW-E Tab	0.03		11
LOW-E UK	SlabShield			
Sigma Technologies	irWRAP			
	3100 Series Radiant Barrier	0.05		
Fi-Foil Company	Silver shield radiant barrier			
	FSK Shield			
	Radiant Shield			

Manufacturer	Product	ε	ε_{aged}	Thickness (mm)
Glidevale limited	Protect VC foil ultra			
Carolina Energy Conservation	ECO-Guard PLUS			
Energy Efficient Solutions	ARMA foil	0.05		4
	ARMA foil VB	0.05		4
Innovative Insulation	Super R Diamond	0.05		
	Super R Platinum	0.05		
	Super R Plus	0.05		
	Tempshield single bubble	0.05		1/8 inch
	Tempshield double bubble	0.05		1/8 inch
SA.M.E. S.r.l.	Isoliving	0.06		8
DuPont	Airguard	0.04		0.43
Polyair	Performa 4.0	0.03		4
	Performa 7.0	0.03		7
Reflectix	Double reflective insulation	0.06		5/16 inch
	Single reflective insulation	0.06		5/16 inch
	Concrete slab insulation			5/16 inch
	Radiant barrier	0.03		

3.2.4 Opaque paints

Paint products do not show the same low emissivity values as the foil products. However, they can be applied to areas where it is hard to use foil products. When applying low-e paints it is also important to avoid inhalation of paint which may have negative health effects. In this study, paints that have been approved as an IRCCS by RIMA, i.e. emissivity below 0.25, have been included. Table 4 shows literature data for low-emissivity paints.

Table 4 Literature data for manufacturers of low-e paints.

Manufacturer	Product	ε	Binder	Solvent	VOC (g/L)
SOLEC	LO/MIT-I	0.21-0.37	Silicone	Xylene	664.41
	LO/MIT-II	0.21-0.37	Silicone emulsion	DI Water	172.73
	LO/MIT-II MAX	0.15-0.17	Silicone emulsion	DI Water	215.48
	SOLKOTE	0.20-0.49	Silicone polymer	Xylene	812
STS Coatings	HeatBloc-Ultra	0.19			< 50
Carolina	ECO-Guard	0.15-0.24			

Manufacturer	Product	ε	Binder	Solvent	VOC (g/L)
Energy Conservation	Coating				
BASF Corporation	Radiance e-025	0.23			212
Henry company	LiquidFoil	0.16			185

3.2.5 Comparison

The opaque and transparent products have different areas of application. Even though their purpose is generally the same, i.e. to reduce the conductive heat through radiative heat transfer, they are installed in different manners and have to fulfil some different criteria. Hence, comparing opaque and transparent materials against each other has little meaning.

Opaque materials has to be practical to install and perform well with regard to blocking out radiant heat. Opaque materials generally only have to block radiant heat from the outside, as it has been shown to be most effective in cooling dominated areas, and climates dominated by heating generally has buildings with thicker layers of conventional thermal insulation, further reducing the effect of reflective insulation solutions. Foil products performs better than paintings with respect to emissivity values. Thus, giving better results on energy savings when installed properly. However, paintings have the advantage of being more flexible and can be added to materials before installation in areas where the installation of foils can be impractical, e.g. the inside of hollow bricks and on the exterior surface of buildings.

Transparent materials must perform well with respect to decreasing radiant heat transfer, but at the same time this should not greatly affect the visible transparency. The fact that these products are also used in all various climates as well makes their use more complex. Solar heat gain coefficients in the products found in this study varies from 0.27 up to 0.79, showing that there are large differences in the possible solar heat gained through low-e windows. Hence, it is important to select the correct glazing for the correct climate to increase the overall beneficial energy usage reduction from a glazing. As insulating glazing units have become widespread due to stricter energy requirements, soft coatings can be used for most low-e glazing products. However, no manufacturer states information on how long one can expect a factory applied coating to perform. Durability and ageing of factory applied coatings are also not so much mentioned in the literature searched through within this study.

Very few manufacturers actually state the emissivity value of their factory applied coatings. From the manufacturers' given values the emissivity for soft coatings can be as low as 0.013 and hard coatings will generally be slightly higher. Based on these low values, it is obvious that the self-applicable films and paints have higher emissivity values, i.e. as observed when comparing the values in Table 2 and 4 with the values in Table 1 and 3. However, by comparing the emissivity values of self-applicable films and paints to the emissivity of float glass (0.837), it is still a major improvement.

3.3 Low-emissivity related standards

It is of interest to know how the emissivity values have been tested with respects to their initial performance, life-time expectations and energy saving potential. This chapter will view some of the standards that mention testing and evaluation of energy performance of low-e materials. The standards described in this study are the standards and testing methods that have been used by the various manufacturers of low-e products mentioned in Tables 1-4.

Emissivity alone cannot describe the overall energy-efficiency of a building element. Thus, the standards cover more than just emissivity and are more focused on characteristics that describe the overall energy-efficiency of glazing units and other materials. However, a low-e coating or material will always be dependent on the local climate and angle of solar radiation. Hence, when total energy usage over a whole year is to be considered climate data have to be taken into account along with the calculated values from the given standards.

"EN410 - Glass in building - Determination of luminous and solar characteristics of glazing" describes solar characteristics and provides a basis for lighting, heating and cooling calculations for glazings (European Committee for standardization [14]).

"EN 12898 - Glass in Building - Determination of the emissivity" specifies procedures for determining the emissivity at room temperature for the surfaces of glass and coated glass. The determination of the emissivity is important for evaluating the total U-value and solar transmittance of glazing according to EN 673 . This standard does however have some limitations. The procedure used is based on spectrophotometric regular reflectance measurements at near normal incidence on non-infrared transparent materials, and is not applicable to glazing with (i) rough or structured surfaces where the incident angle is diffusely reflected, (ii) curved surfaces where the incident radiation is regularly reflected at angles unsuitable to reach the detector while sing regular reflectance accessories and (iii) infrared transparent (European Committee for standardization [13]).

"EN 1096-3 - Coated glass - Part 3: Requirements and test methods for class C and D coatings" specifies requirements and test methods related to resistance to solar radiation for coated glass for use in buildings. These tests evaluate if exposure to solar radiation over an extended period of time produces appreciable changes in light transmittance, solar transmittance and reduction in IR-reflectance for low-e coatings.

The National Fenestration Rating Council (NFRC) is a non-profit organization that provides independent rating and labelling systems for windows, doors and skylights. The ratings given include U-values, visible transmittance, solar heat gain coefficients and air leakage, as well as an energy rating systems for both existing and emerging fenestration products. The NFRC is an accredited standard developer and helps develop American national standards. Most manufacturers situated in America refers to the NFRCs test methods and energy labels for their products tested values.

"ISO 10292 Glass in building - Calculation of steady-state U values (thermal transmittance) of multiple glazing" explains how to obtain the normal and corrected emissivity for coated surfaces from spectrometer measurements, and how these values are used in the total U-value calculation (International organization for standardization [27]).

"ISO 15099 - Thermal performance of windows, doors and shading devices - Detailed calculations" specifies detailed calculation procedures for thermal and optical transmission properties of window and door systems. Herein detailed calculation methods for both single and multi-layer glazing units with low-e coatings (International organization for standardization [28]).

4 Low-emissivity materials as part of an energy-efficient solution

4.1 General

Low-e materials has been shown to give a decrease in energy usage in buildings. Figure 5 shows areas where opaque materials can be implemented to help conserve energy. In addition, there is also the benefits from using low-e materials for windows.

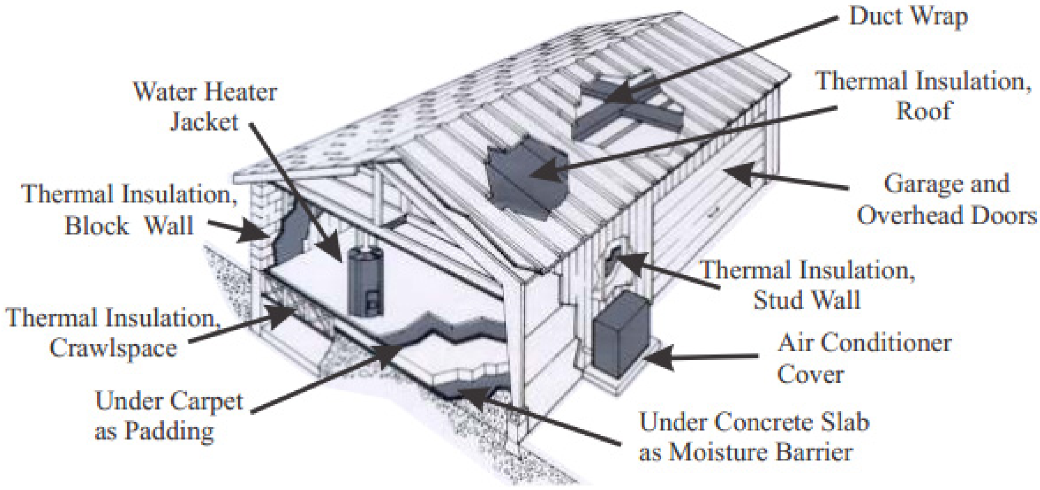

Figure 5 Areas where low-e materials can be applied for energy savings (low-e reflective insulation [47]).

4.2 Windows

In recent years, it has become more common to design buildings with extensive glass facades. Hence, the focus on more energy-efficient glazing solutions has increased to meet the challenge of reducing heating and cooling loads. For residential buildings windows will typically account for about 30-50 % of transmission losses through the building envelope. While U-values for walls, roofs and floors can be between 0.1-0.2 W/(m^{2}K), the best windows may often have a U-value of 0.7-1.0 W/(m^{2}K) (Gustavsen et al. [23]). Windows also provides an opportunity to gain free energy from the sun, and improve both thermal and visual comfort for a buildings residents. Effectively taking advantage of free solar energy gives the potential for higher energy-efficient windows. By applying a low-e coating to a window, the thermal conductance due to radiation between glass pane surfaces can be reduced to about 0.1 W/(m^{2}K) (Manz [48]).

Considering a low-e window for building applications is not straight forward. Figure 6 shows that a low-e window can still have large differences in solar-gain. Hence, the energy balance between solar gain and transmission losses makes calculating window performance more complex. This means that the use of low-e windows has to be planned with consideration to the local climate of the building. Choosing a window with a low-e coating, but a solar-gain coefficient that is not suited for the climate, might neutralize the possible energy gains from the low-e coating. Thus, giving a window which saves no energy. When the correct window for a climate has been decided, the orientation of the facades will also affect the effect of a low-e window, as emissivity is also dependent on the incident angle.

Another drawback of low-e coatings is the reduction in transmission of visible light. The reduction of visible light will lead to an increased need for artificial lighting, giving a higher energy usage. This problem is still the focus of ongoing research. A solution for this includes the adding of antireflective covering, which has been shown to increase the visible transmittance (Rosencrantz et al. [65], Hammarberg and Roos [24]).

For windows to meet todays energy standards a low-e coating alone is not sufficient. The low-e coating is commonly combined with multi-layered glazing units, and can also be combined with other solutions, e.g. reflective or anti-reflective coatings, solar control films and coatings and evacuated glazing.

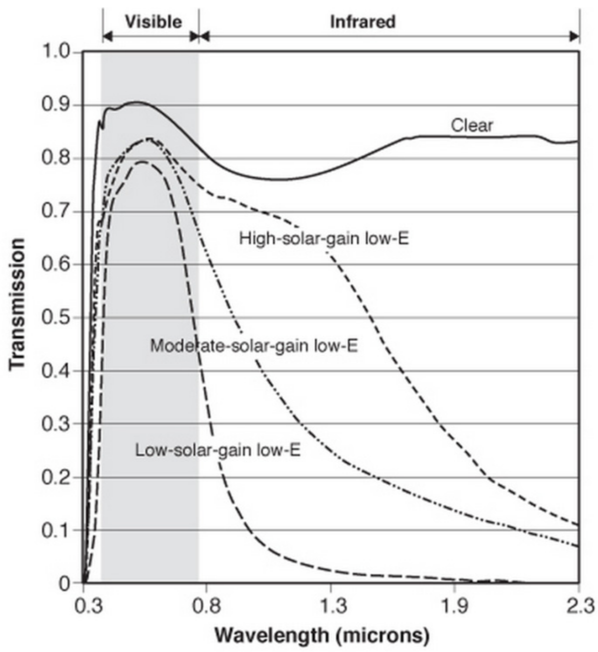

Figure 6 Transmission vs wavelength for low-e windows (Commercial Windows [11]).

Low-e coatings may provide other beneficial effects on glazing besides the increase in energy efficiency.

4.2.1 Anti-condensation windows

A common problem with new thermal insulating glass units is the formation of condensation on the outside of the window. Low-e coatings on the outward facing surface can help to prevent condensation, and allow windows to keep their desirable visual performance for longer parts of the year. Werner and Roos [74] have performed simulations on windows with external low-e coatings. Furthermore, it has been discussed how further improvements may be made to improve anti-condensation properties by applying low-e coatings.

Note that these low-coatings has to be weather resistant as it is placed in outside environmental conditions. These low-e coatings will not have the same low emissivity value as soft coatings placed inside the cavity of a multi-layered glazing unit (Gläser and Ulrich [19]).

4.2.2 Vacuum glazing

Evacuated insulating glazing units, i.e. vacuum glazing, provides high thermal resistance. Though vacuum glazing provides a significant improvement in heat loss reduction, they will still benefit greatly from the adding of a low-e coating (Eames [12], Fang et al. [16]).

4.2.3 Ageing effects

As mentioned earlier, soft coatings are not nearly as durable as hard coatings. Soft coatings needs to be placed inside the cavity of an insulating glass unit. The more durable hard coating which can be placed towards open areas, even though more robust, will face harsher climate stress. It is of interest to know if these factory applied coatings can maintain the initial emissivity over the expected lifetime of the window, and if ageing of the low-e coating impairs the visible transmittance.

Studies have been conducted on the effects of moisture on soft low-e coatings. As most soft coatings are applied with silver as the metal layer, it is important to avoid excess of air and moisture to prevent oxidation. A known problem with silver based soft coatings is white-dot defects on the coating surface due to exposure to moisture (Ando et al. [2]). Degradation usually takes place because moisture penetrates the first dielectric layer and induces silver migration, resulting in a peel off of the top oxide layer. Ando and Miyazaki [3] showed that the durability of low-e coatings in humid environments is closely correlated with the internal stresses in the oxide layers. However, this gives no results on how the coating performs under working conditions, i.e. inside a mounted insulating glazing unit with parameters matching the environment in the cavity.

4.3 Walls

The use of low-e solutions in opaque parts of walls are mainly beneficial in regions dominated by overheating. The building norms in these areas are usually distinguished by little conventional thermal insulation, i.e. thin or no layers of mineral wool, EPS etc. Temperatures in such constructions will rapidly increase in periods with high solar energy flux. Hence, adding low-e solutions to reflect this heat away will prove more effective.

Laboratory, field measurements and simulations have been conducted on the energy saving effect of opaque low-e materials in different wall structures in various climates (Joudi et al. [42], Saber et al. [66], Shi and Zhang [69]).

Foil and paint products have been described briefly in previous chapters. In the following, some of the possible areas of application to wall constructions and application to materials will be shown. Paints especially have a lot of interesting and innovative uses that can be explored to increase the overall thermal resistance of constructions without affecting the construction process.

Hollow bricks with low-e paint

Principi and Fioretti [61] investigated the use of low-e painting on the inner surfaces of hollow bricks (Fig. 7). The reduction in the emissivity of the internal surfaces would lead to a reduction in thermal radiation heat transfer. For the conducted tests, a low-e painting with an emissivity value of approximately 0.5 was used. The test results showed a 20 % reduction in the thermal conductivity of the brick. It was also concluded that low-e coatings proved to be an easy and cheap technology to improve the thermal resistance of hollow bricks, as it can be applied without substantial modification in the manufacturing of the bricks.

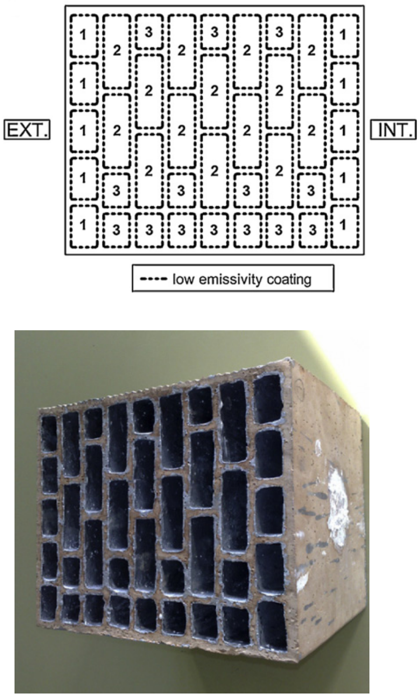

Figure 7 Hollow brick with low-e coating on the inner surfaces, schematic drawing (top) and photo (bottom) (Principi and Fioretti [61]).

Coated surfaces

Studies have been conducted on the effect of adding anti-reflective coatings to the exterior cladding and the interior surfaces of walls, or at both surfaces at the same time. In a cold climate, adding reflective coatings to the interior surface was shown to give savings to the total energy usage as the required heating loads could be reduced. However, an increase in cooling loads during the summer was shown. For an exterior reflective surface coating in a cold climate, the energy usage ended up being larger than for a similar uncoated building. In warm climates the results were reversed, exterior reflective surface coating gave energy savings, while interior reflective surface coating gave an increase in energy usage (Joudi et al. [41]). Other studies also highlight the effects of coatings between different climate regions (Guo et al. [22]).

Foils

Installing foils into a building construction requires sufficient airspace on either side of the foil product (Fig. 8). If the foil product is in direct contact with materials on both sides, the heat will be transferred through solid conduction and be unable to block radiative heat. Hence, gaining no benefits from the low emissivity of the materials surface.

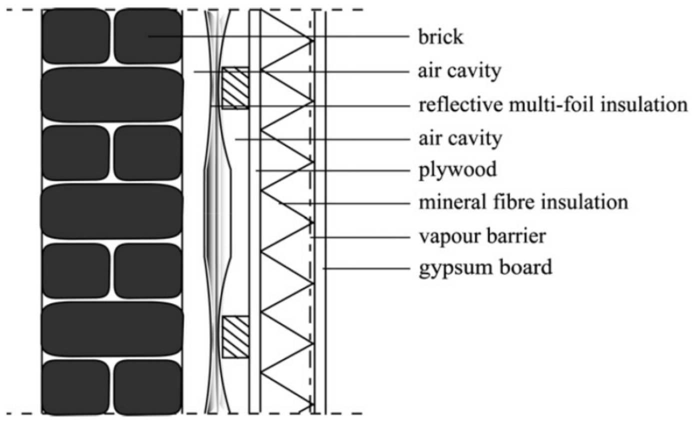

Figure 8 Reflective foil installed inside a wall cavity (Tenpierik and Hasselaar [72]).

Low-e foils as vapour barriers

It is common to use polyethylene foils as a vapour barrier in wood frame constructions. The surface emissivity of PE-foils is typically around 0.9. By exchanging the PE-foil with an aluminium-polyethylene sheet with lower surface emissivity it has been found that the thermal resistance of a wall construction can be increased. However, the overall effect of such a construction is something that should be further investigated (Pasztory et al. [60]).

4.4 Roofs

Roofs are exposed to large amounts of solar energy throughout the year, especially in warm climates. The excessive amounts of solar energy will heat up attics or top floors (Fig. 9), leading to overheating and a need for more use of air-conditioning to keep a comfortable indoor temperature. The application of radiant barriers to conserve energy in residential buildings has received considerable attention in recent years. Asadi et al. [5] developed a simplified tool for calculating the energy performance of installing a radiant barrier to an attic. This tool showed that the highest rate of energy saving with an installed radiant barrier occurs in hot and humid regions, and also where there is little else thermal insulation installed. The increased surface temperature of the radiant barrier increases its effect. In colder climates the potential for energy savings were low.

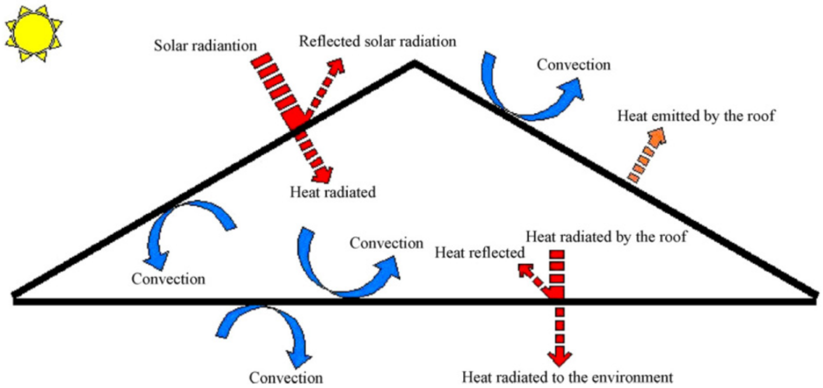

Figure 9 Heat transfer mechanisms in an attic space (Michels et al. [51]).

When installing a radiant barrier to a roof construction, as with walls, it is important to create sufficient air space on at least one side of the radiant barrier (Fig. 10). The surface of the radiant barrier must also be placed in a way which does not allow dust or dirt to form on the surface as this will reduce the effectiveness, i.e. increase the emissivity, of a radiant barrier.

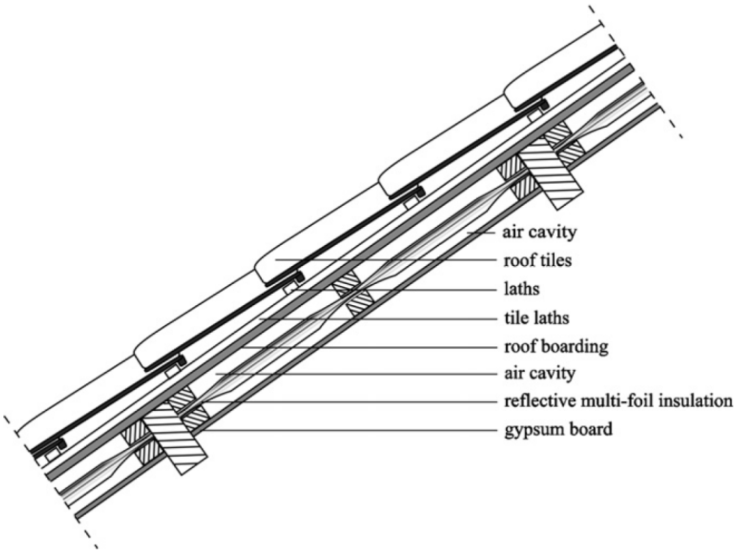

Figure 10 Reflective foil installed inside a cavity in a roof construction (Tenpierik and Hasselaar [72]).

Another approach when using low-e materials in roofs is to install them at the roof surface. This way the roof will reflect off a large amount of the heat from the solar radiation. Hence, maintaining a cooler surface temperature which will slow down the heat conduction through the roof (Akbari [1]). However, no studies have been conducted to measure how climate conditions will affect the performance due to ageing effects of such a solution.

Measurements on various types of roof installations using reflective insulation have been conducted (Belusko et al. [7], Miranville et al. [53], Muselli [57], Saber [67], Saber [68], Suehrcke et al. [70]). Some of these studies also attempt to give an experimental evaluation of performances from field measurements. Furthermore, see also the numerical simulation study by Murphy et al. [78], addressing the potential energy savings for cool roofs in cold climates (dark versus light roof colours).

4.5 Floors

To the authors knowledge, the use of reflective insulation in flooring has not been studied so much. Earlier, some manufacturers who provide slab shields, e.g. low-e materials for concrete floors, were shown. These products have the extra benefit of also working as a vapour barrier if they are left unperforated. However, there are few studies which shows the results and effects of low-e floor materials and products. Under floors the convection is in most cases rather small, i.e. stagnant air. With a sufficient air gap, it follows that most of the heat will be transferred by thermal radiation (Uvsløkk and Arnesen [73]). Installing a low-e material towards such an air gap may yield benefits towards decreased energy usage.

4.6 Climate considerations

The actual application and energy saving potential of low-e materials will be different for different climates, e.g. hot versus cold climate. Parts of these issues are already discussed briefly in the foregoing chapters. Although energy calculations with respect to various climates are not within the scope of this study, some of these aspects are discussed further in the following. As at many locations the climate exposure is changing very much during the year, e.g. with respect to both average and extreme temperatures, detailed studies by e.g. numerical calculations may have to be carried out in order to evaluate the best application of various low-e materials and solutions and their potential energy savings throughout the year.

The exact calculations and evaluations also considering climate variations with respect to location (e.g. climate zone) and seasonal variations (e.g. winter versus summer) may differ a bit whether (opaque) wall, roof or floor constructions are being treated. Furthermore, whether the walls are facing south, north, east or west may also be of importance. For transparent or translucent windows or other glazing structures, the calculations and evaluations also have to consider the low-e properties in the infrared (thermal) radiation wavelength region versus the miscellaneous solar radiation glazing factor properties in the solar radiation region, where a trade-off or optimization between various properties often has to be made. For example, in general a low-e window coating will not only reduce the thermal radiation loss, but also decrease the solar radiation throughput, the latter one often characterized by e.g. the visible solar transmittance (T_{vis}), the solar transmittance (T_{sol}) and the solar heat gain coefficient (SHGC, a.k.a. solar factor (SF) and g-value).

Currently, all the commercial low-e materials are static materials, i.e. their emissivity can not be changed (except due to ageing and degradation) when first manufactured, selected and installed. That is, the user can not dynamically control the emissivity when in use in buildings. Hence, it is important to select specific emissivity values which give the best and optimum overall performance with regard to energy savings and user comfort throughout the lifetime of the low-e material (which will preferably be the same as the lifetime of the building) at the anticipated climate conditions at the chosen location. As the climate is expected to change (e.g. to a harsher climate) in the coming years, this aspect should also be considered and preferably accounted for. If (or when) one may manage to make materials with a controllable emissivity being able to reach both low and high emissivity values, this will offer new opportunities in building applications. In this respect, it should be noted that materials for a dynamic control of the solar radiation transmittance through windows, including commercial products, do already exist, i.e. electrochromic windows (Baetens et al. [6], Jelle et al. [34], Jelle [38]). See also ch.5.3.4 for further aspects on this topic.

5 Future research perspectives

5.1 Improving the current technology

5.1.1 Improving low-e coating properties

As of today, low-e coatings on commercial products give emissivities as low as 0.013. Further improvements on this may be possible by testing other combinations of dielectrics and metals, and alter the configurations with more film layers and different thicknesses (Leftheriotis and Yianoulis [45]). However, the energy saving potential of reducing the emissivity value further may be minimal and not benefit in more than a few kWh/m^2 a year (Karlsson and Roos [43]). Considerations should therefore be made towards new combinations of materials and production methods that can produce the same emissivity but with lower production costs. New combinations through various thicknesses of the layers in a low-e coating based on silver were tested out experimentally by Le et al. [44]. The aim was to identify an optimal deposition process with consideration to the thickness of the various stacks in the coating layers.

5.1.2 Increasing visible transmittance

A goal for low-e coatings used on transparent materials should be to achieve the same transparency as clear glass. As of today, the reduction in visible transmittance when applying low-e coatings is considered an undesirable characteristic, as it may increase the need for artificial lighting, i.e. increase energy usage (Jelle et al. [34]).

One option that has been tested out is to add anti-reflection treatment to low-e coatings. Hammarberg an Roos [24] showed that it was possible to increase the visible transmittance by up to 9.8 % by depositing a thin film of silicon dioxide on both sides of a commercial glazing. This study also pointed out that it is probable that an even larger increase of visible transmittance can be achieved if the sol-gels used for the antireflective layers could be optimized regarding the refractive index.

5.1.3 Angular selectivity

The use of angular selective solar control is already implemented by using prismatic glass or louver systems that block out direct sun light at specific angles while diffuse sky-light is admitted. Systems like these can be used to block certain angles in periods where the sun gives off most of its energy and overheating happens. However, these systems impair the visibility through the facade. If the same principle could be implemented with coatings, one could possibly achieve a higher visible transmittance while at the same time allowing passive use of the winter sun to reduce heating loads and blocking out summer sun to reduce cooling loads in the same glazing unit. The result would be closer to the perfect window (Fig. 11) as described by Ye et al. [76]. However, this would mean that coating must be tailored to a specific building site and orientation. Thus, creating a need for more detailed planning to select a correct coating for optimization of energy savings. Naturally, in addition to the solar radiation energy aspects, glare aspects for windows should also be considered, i.e. disturbances to the human eye from transmitted or reflected visible solar radiation.

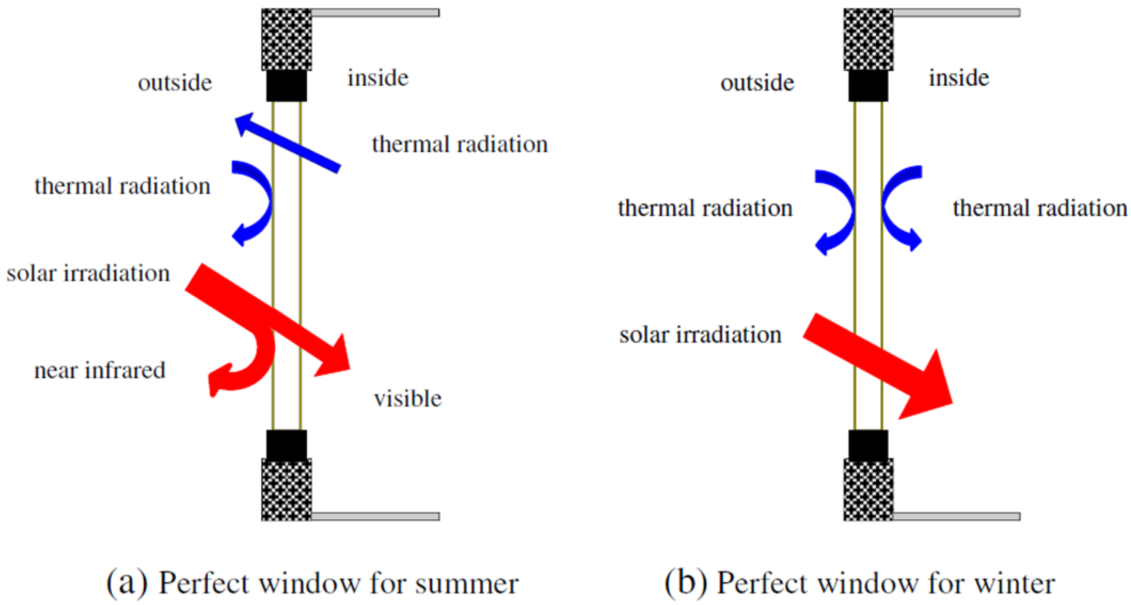

Figure 11 Schematic of a 'perfect' window during summer and winter (Ye et al. [76]).

5.1.4 Improving film technology

Films have one major advantage compared to the factory applied coatings. That is, the film can be produced without the glass at hand. Hence, they can be manufactured separately and at the same time. However, the films of today do not perform as well as factory applied coatings. The possibilities of improving the film technology and make it achieve the same level of performance as factory applied coatings may make for a process where low-e glazing can be manufactured faster and at a lower cost. It also open up possibilities to apply low-e properties to already installed glass without coatings.

Today, films are applied to the surface toward the interior of a building. If films can achieve the same level of performance as coatings, they may become a part of the manufacturing process of multilayered glazing and be applied inside the cavities as well.

5.2 Durability and ageing

Few studies have been conducted on the effect of ageing on low-e coatings and materials over. The importance of ageing effects on the thermal performance of low-e materials is something that should be investigated with regard to the potential of energy savings over a components lifetime in a construction. Questions which needs to be answered is how a reduction in emissivity value affects energy usage and dimensioning of air conditioning and the need for room heating. None of the manufacturers in this study states an aged value for their products' emissivity values, showing that there is a need to look into ageing effects. Note also the more general accelerated climate ageing studies by Jelle [32] and Jelle et al. [33], where the former one also addresses the importance of performing accelerated climate ageing of new materials and solutions.

Soft coatings with silver as the metallic layer has been shown to be very vulnerable under atmospheric conditions when exposed to solar irradiation, but unaffected if it is kept in a moderate vacuum (Leftheriotis and Yianoulis [45]).

5.3 New low-emissivity materials and technologies

5.3.1 New materials

It has been mentioned that one of the drawbacks of low-e coatings is the decrease in visible transmittance. Currently, anti-reflection coatings are being applied to increase the visible transmittance without impairing the effect of the low-e coating. Further increasing the visible transmittance of low-e windows is still a field of interest. Gao et al. [18] discussed the anti-reflective properties of monodisperse hollow silica nanospheres and its application to windows. The spheres showed interesting optical properties and gave a decreased reflection. The anti-reflective performance of hollow silica nanospheres may still be further modified and is worth pursuing.

A possible approach to prepare new opaque low infrared emissivity materials have been investigated by Zhang et al. [77]. This approach was based on a nacre biomimetic design mimicking the highly organized brick-and-mortar structure of nacre, a kind of nacre-like organic–inorganic composite material of polyurethane (PU)/flaky bronze composite coatings. The structures designed in this experiment obtained infrared emissivities as low as 0.206.

Other material choices for low-e coatings that have been investigated include coatings based on diamond like carbon (Chiba et al. [9]) and tin doped indiumoxide (Reidinger et al. [62]).

5.3.2 New glazing technologies

There are several other technologies in development that aims to control solar heat gain and at the same time have the ability to adapt to seasonal variation. One such promising technology is electrochromic windows. Together with a low-e coating this will have the benefit of low radiative conductive heat transfer along with the possibility to alter the solar heat which passes through the glazing for seasonal as well as daily variations. The efficiency of electrochromic windows has already been proven in hot climates, but more research is necessary to validate the effects in colder climates (Baetens et al. [6]). Another study performed by Fang et al. [17] have tested the thermal performance of electrochromic low-e glazing with an evacuated glazing unit, which may be the way forward to provide high-performance windows for tomorrow.

With respect to various glass surface coating technologies, the material development and studies on e.g. electrochromic materials (Baetens et al. [6], Jelle and Hagen [29-30], Jelle et al. [31] and Jelle [38]), self-cleaning glazing (Midtdal and Jelle [52]), building integrated photovoltaics (Jelle et al. [35] and Jelle and Breivik [36-37] and snow and ice related issues for e.g. solar cell panels (Jelle [39]) should be noticed. The robustness of these materials should also be addressed and evaluated (Jelle et al. [40]).

5.3.3 New manufacturing process for coated windows

The current manufacturing method, along with the cost of silver, of low-e coatings is a reason for the relative high costs of low-e coatings. A new process for coating based on solution derived nanocomposite (SDN) technology has recently been investigated (Niitsoo et al. [58]).

5.3.4 Controllable and adaptive emissivity

All current commercial low-e materials are static materials, i.e. their emissivity remains the same (except an anticipated increase due to ageing) and can not be changed by the users (see also the discussion in ch.4.6). Thus, the static and traditional low-e materials can not be adjusted to e.g. climate variations and changes and are therefore not able to meet various energy saving and user comfort demands at a optimum. Nevertheless, one may envision the possibility of making materials with a controllable or adaptive emissivity. The different chromogenic materials like electrochromic (controllable), photochromic (adaptive) and thermochromic (adaptive) represent an interesting analogous class of materials which actually also exist as commercial products. The controllable materials have in principle a larger potential than the adaptive ones, as the user may decide (control) exactly (within the limitations of the specific material) the desired properties e.g. by application of an electrical voltage, whereas the adaptive materials change their properties according to some non-controllable external forces like e.g. the solar radiation and temperature. It can be shown that the reflectance of materials, and thus also the emissivity (see Eq.4), may be changed by changing the so-called plasma wavelength λ_p given by the following (Jelle [38]):

$$\lambda_p = 2\pi c / \omega_p = (2\pi c/q_e)(m_e \varepsilon_0/n_e)^{1/2} \qquad (5)$$

where ω_p, c, q_e, m_e, ne and ε_0 denote the plasma frequency, the velocity of light, the electron charge, the free electron effective mass, the free electron density and the dielectric coefficient of vacuum, respectively. Materials with a high free electron density (short λ_p) will be highly reflecting materials with a low emissivity, whereas a low free electron density (long λ_p) corresponds to a low reflectivity and thus a high emissivity. By changing λ_p, i.e. changing the free electron density, one may regulate the reflectance with an adjustable vertical reflectance edge, where λ_p is located at just this vertical reflectance edge. For further information on these aspects it is referred to the study by Jelle [38] and references therein. Hence, there may be possibilities and future opportunities for designing and making materials with a controllable (or adaptive) emissivity.

5.4 Future perspectives on building implementations of low-emissivity materials

5.4.1 New energy labelling for windows

State-of-the-art low-e windows utilize solar energy in different ways. Some have a high solar heat gain while others reduce the solar heat gain. However, there are many energy labels that only consider a windows total U-value, and neglects the solar heat gained or blocked. The common norm for window labelling should account for both thermal losses and solar heat gains for various climates. Grynning et al. [21] have performed a study where the effects of considering the solar heat gain is shown for windows in an office building in Oslo, Norway. Variation between summer and winter shows that choosing the optimal solar heat gain coefficient is a challenge, as high solar heat gain is beneficial in the colds part of the year, while low solar heat gain is beneficial in the warm parts of the year.

Further improvements to labelling systems could also include parameters that consider increase or decrease in the need for artificial lighting and the influence of orientation and size of windows. This will give valuable information to the consumers, and would also show the benefit of a low-e coating and other energy-efficient window solutions. Labelling based on some of these principles are already seen in the UK, Denmark, Finland, Czech Republic and Slovakia (Cazes [8]). There are many other solar radiation glazing factors that may be of interest when selecting windows for specific purposes, see e.g. the comprehensive study by Jelle [38].

5.4.2 Predicting the correct U-values for low-emissivity products in use

Saber [67] investigated the thermal performance of low-emissivity foils and how they reacted to changes in emissivity and different angles. This investigation gave a recommendation that future work should be focused on determining actual R-values of reflective insulation in combination with other insulation materials and climactic conditions. This will reduce the risk of over sizing heating or cooling equipment and help to better determine condensation risks. Several other studies also debate the actual U-values of reflective insulation and the difficulty in determining these precisely (Tenpierik and Hasselaar [72], Belusko et al. [7]).

5.4.3 Investigating the use of low-emissivity materials in floor constructions

As mentioned earlier, few studies have been found to address the possible benefits of low-e materials in floor constructions. This subject may hold interest for further investigations.

Conclusions

This study has found that low-emissivity (low-e) solutions for glazing is a widely accepted and used solution with a proven effect on energy efficiency. Positive results have been shown in most climates. These low-e coatings are a great way to passively reduce energy usage. Hence, there is a wide variety of manufacturers on the market offering a wide variety of products suited for various climates. Many countries have made low-e coated windows a part of new building norms in order to further reduce energy usage of buildings. Most likely the use of low-e coated glazing will continue to increase in other countries as well.

Opaque materials, however, are not as widely spread as transparent low-e products. Many studies have been conducted which shows the positive effects in several different climates. Where low-e glazing requires no changes in the way of constructing, opaque solutions require changes to the structure or appearance of a building. Especially so with foils mounted inside the building envelope, as they require sufficient airspace to perform adequately. As there is still ongoing debate on how to best determine the exact U-values of low-e products under building related conditions, there is still more research to be carried out. More exact U-values will be beneficial both to increase use of low-e products and to prevent over-dimensioning of heating or cooling systems.

For future research, an important goal should be to evaluate how low-e products perform with regard to ageing. Change in emissivity due to ageing may change the overall energy usage of buildings, and is hence a crucial factor when performing life cycle energy calculations.

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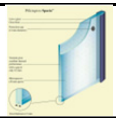
Appendix

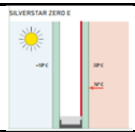
Table A1 Glass coatings/factory coated glazing.

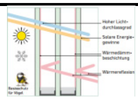
Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* (W/(m^{2}K))	U_g* (W/(m^{2}K))	Additional information
Guardian Climaguard 2300 Harmon Rd. Auburn Hills, MI 48326 USA Tel: +1 855 660 5905 ClimaGuardProductInfo@Guardian.com http://www.climaguardglass.com	ClimaGuard 55/27					55	18	0.28		0.29 Air fill		http://www.climaguardglass.com/ProductSolutions/Energyefficientproducts/ClimaGuard5527/index.htm (Accessed 27.06.2013)
	ClimaGuard 62/27					62	5	0.27	Triple silver soft coat	0.29 Air fill		http://www.climaguardglass.com/ProductSolutions/EnergyEfficientProducts/ClimaGuard6227/index.htm (Accessed 27.06.2013)
	ClimaGuard 63/31					63	24	0.31		0.29 Air fill		http://www.climaguardglass.com/ProductSolutions/EnergyEfficientProducts/ClimaGuard6331/index.htm (Accessed 27.06.2013)
	ClimaGuard 70/36					70	30	0.36		0.29 Air fill		http://www.climaguardglass.com/ProductSolutions/EnergyEfficientProducts/ClimaGuard7036/index.htm (Accessed 27.06.2013)
	ClimaGuard 71/38					71	24	0.39		0.29 Air fill		http://www.climaguardglass.com/ProductSolutions/EnergyEfficientProducts/ClimaGuard7138/index.htm (Accessed 27.06.2013)
	ClimaGuard 80/70					81	41	0.70		0.32 Air fill		http://www.climaguardglass.com/ProductSolutions/EnergyEfficientProducts/ClimaGuard8070/index.htm (Accessed 27.06.2013)
Pilkington/ Nippon Sheet Glass Co., Ltd. 5-27, Mita 3-chome, Minato-ku, Tokyo 108-6321 Japan http://www.pilkington.com	K Glass		0.16			76		0.78	Hard coat		1.5 Argon fill	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/kglass/default.htm (Accessed 19.06.2013)
	K Glass S					81		0.75	Soft coat		1.2 Argon fill	Determined in accordance with EN410 and EN673 http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/kglass/product-range/k-glass-s/default.htm (Accessed 19.06.2013)
Pilkington/ Nippon Sheet Glass Co., Ltd. 5-27, Mita 3-chome,	K Glass OW					78		0.79	Hard coat		1.5 Argon fill	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/kglass/product-range/k-glass-ow/default.htm (Accessed 19.06.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* ($W/(m^2K)$)	U_g* ($W/(m^2K)$)	Additional information
Minato-ku, Tokyo 108-6321 Japan http://www.pilkington.com	Optitherm S1		0.013						Soft coat		1.0	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/energikare/default.htm (Accessed 19.06.2013)
	Optitherm S3		0.037			80			Soft coat		1.1	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/energikare/energikare-range/triple/default.htm (Accessed 19.06.2013)
	Insulight Therm											http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/insulighttherm/default.htm (Accessed 19.06.2013)
	Spacia				62	78		0.67			1.1	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/thermalinsulation/energikare/energikare-range/legacy/default.htm (Accessed 19.06.2013)
	Anti-condensation				60	70		0.71	Hard coat		1.5 Argon fill	http://www.pilkington.com/europe/uk+and+ireland/english/products/bp/bybenefit/specialapplications/anti-condensation+glass/default.htm (Accessed 05.12.2013)
PPG Industries, Inc. Glass Business & Discovery Center 400 Guys Run Road Cheswick, PA 15024 Tel: 1-888-PPG-GLAS www.ppgglass.com	Sungate 400					78	32	0.68		0.28		Given numbers based on NFRC methodology http://www.ppgresidentialglass.com/lowe_glass/low-e-windows.aspx (Accessed 04.12.2013)
	Sungate 500					76	49	0.70	Hard coat	0.31		
	Sungate 600					73	45	0.70		0.29		
	Solarban 60					72	21	0.39		0.25		
	Solarban 67					55	13	0.29		0.25		
	Solarban 70XL					64	6	0.27		0.24		

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* ($W/(m^2K)$)	U_g* ($W/(m^2K)$)	Additional information
Walshsglass 198 Bannister Road Canning Vale WA PO Box 1022 Canning Vale Western Australia 6155 Australia Tel: 08 9366 6666 Fax: 08 9455 2640 sales@walshsglass.com.au www.walshsglass.com.au	Evantage				41	56	19	0.53			1.7 Air fill	http://www.walshsglass.com.au/upload/pages/performance-data_20120417110627/performance-data-information---twin-seal-igu-with-energytech.pdf?1377489802 (Accessed 27.06.2013)
	Sunergy				40	57	31	0.50			1.8 Air fill	
	EnviroShield				33	61	1	0.43			1.7 Air fill	
	ComfortPlus				42	66	1	0.54			1.5 Argon fill	
Cardinal Glass Industries Eden Prairie, MN 775 Prairie Center Dr # 200, 55344 USA 952.229.2600 952.935.5538 info@cardinalcorp.com www.cardinalcorp.com	LoE-366					65	5	0.27	Soft coat	0.29[a] Air fill		http://www.cardinalcorp.com/products/coated-glass/loe3-366-glass/ (Accessed 04.12.2013)
	LoE-270					70	14	0.37		0.30[a] Air fill		http://www.cardinalcorp.com/products/coated-glass/loe2-270-glass/ (Accessed 04.12.2013)
	LoE-272					72	16	0.41		0.30[a] Air fill		http://www.cardinalcorp.com/products/coated-glass/loe2-272-glass/ (Accessed 04.12.2013)
	LoE-180					79	29	0.69		0.31[a] Air fill		http://www.cardinalcorp.com/products/coated-glass/loe-180-glass/ (Accessed 04.12.2013)
	LoE-240					40	16	0.25		0.30[a] Air fill		http://www.cardinalcorp.com/products/coated-glass/loe2-240-glass/ (Accessed 04.12.2013)
	LoE-i89											http://www.cardinalcorp.com/products/coated-glass/loe-i89-glass/# (Accessed 04.12.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* (W/(m^{2}K))	U_g* (W/(m^{2}K))	Additional information
AGC GlassEurope 166 Chaussée de La Hulpe 1170 Brussels, Belgium Tel: +32 2 674 31 11 Fax: +32 2 672 44 62 headquarters@eu.agc.com www.yourglass.com	Planibel G					75		0.73	Hard coat	1.9 Air fill		http://www.yourglass.com/agc-glass-europe/gb/en/low-emissivity_glazing/planibel_low-e/brand_summary.html (Accessed 04.12.2013)
	Planibel TOP					81		0.67		1.3 Argon Fill		
	Planibel LOW-E Antifog					72	17	0.63			1.1 Argon Fill	http://www.yourglass.com/agc-glass-europe/gb/en/lowe/antifog/brand_description.html (Accessed 21.06.2103)
Saint-Gobain Glass 66 Kornish El Nile, Zahret El Maadi Tower, Floor 38, Helwan Egypt Tel: +202 25288070/75 Fax: +202 25288072 mktg.sgge@saint-gobain.com http://eg.saint-gobain-glass.com	SGG Planitherm Total					79	35	0.63			1.7 Air fill	http://eg.saint-gobain-glass.com/b2c/default.asp?nav1=pr&nav2=single%20pane&id=2090 (Accessed 04.12.2013)
	SGG Planitherm Total 1.3					77	35	0.66			1.8 Air fill	
	SGG Planitherm Ultra N					80	33	0.63			1.6 Air fill	
	SGG Nano											http://in.saint-gobain-glass.com/b2c/default.asp?nav1=pr&nav2=single%20pane&id=18494 (Accessed 27.06.2013)
Clear Glass Solutions PO Box 26, Maryknoll Victoria 3812 Tel:03 5942 8444 Fax: 03 5942 9286 www.clearglass.com.au	Planibel G					74		0.71	Hard coat		1.9 Air fill	http://www.clearglass.com.au/glass-types/low-e-glass (Acessed 21.11.2013)
	Comfort E2					75		0.72	Hard coat		1.7 Argon fill	http://www.clearglass.com.au/glass-types/low-e-glass (Acessed 21.11.2013)
	Sunergy clear					69		0.62	Hard coat		4.3	http://www.clearglass.com.au/glass-types/low-e-glass (Acessed 21.11.2013)
	Planibel Energy N					79		0.64	Soft coat		1.6 Air fill	http://www.clearglass.com.au/glass-types/low-e-glass/planibel-energy-n-low-e-glass-2 (Acessed 21.11.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* (W/(m^{2}K))	U_g* (W/(m^{2}K))	Additional information
CSG Architectural Glass CSG Building, No.1, 6th Industrial Road, Shekou, Shenzhen, P.R.China Tel: +86-755-26860666 Fax: +86-755-26692755 www.csgglass.cn	Single Silver Low-E											http://www.csgglass.cn/en/193/2/productdetail.html (Accessed 04.12.2013)
	Double Silver Low-E											
	Triple Silver Low-E											
Milgard Corporate 1010 54th Ave East Tacoma, WA 98424 USA Tel: +1 800 645 4273 www.milgard.com	Suncoat Low-E2 glass					70	16	0.37-0.41		0.30		http://www.milgard.com/milgard-advantages/low-e-window-coating.asp (Accessed 27.06.2013)
	SunCoatMAX Low-E3 glass					66	5	0.27		0.29		
Viridian 39 Delhi Rd North Ryde NSW 2113 Australia Tel: 1800 810 403 www.viridianglass.com	EnergyTech					73		0.61	Hard coat		1.6 Argon fill	http://www.viridianglass.com/Products/energytech/default.aspx?ProductType=HouseHolder (Accessed 27.06.2013)
	PerformaTech E					58		0.32			1.33	http://www.viridianglass.com/Products/performatech-e/default.aspx?ProductType=HouseHolder (Accessed 27.06.2013)
	Sunergy					68		0.59	Hard coat		4.1 Single pane	http://www.viridianglass.com/Products/sunergy/default.aspx?ProductType=HouseHolder (Accessed 04.12.2013)
	EVantage					68		0.63	Hard coat		3.8 Single pane	http://www.viridianglass.com/Products/evantage/default.aspx?ProductType=HouseHolder (Accessed 04.12.2013)
	SolTech					73		0.61	Hard coat		1.6	http://www.viridianglass.com/Products/soltech/default.aspx?ProductType=HouseHolder (Accessed 04.12.2013)
	SmartGlass				68	83	54	0.72	Hard coat		3.7 Single pane	http://www.viridianglass.com/Products/smartglass/default.aspx?ProductType=HouseHolder (Accessed 04.12.2013)
	ComfortPlus					82		0.68			3.6 Single pane	http://www.viridianglass.com/Products/comfortplus/default.aspx?ProductType=HouseHolder (Accessed 04.12.2013)
Glaströsch info@glastroesch.ch www.glastroesch.ch	Silverstar Zero E					80		0.60			1.0	http://www.glastroesch.ch/services/datentabellen-ausschreibungstexte/waermedaemmisolierglas-silverstar/silverstar-zero-e-2-fach-isolierglas.html (Accessed 27.06.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	T_{sol}	T_{vis} (%)	T_{uv} (%)	SHGC	Coating	U_w* ($W/(m^2K)$)	U_g* ($W/(m^2K)$)	Additional information
	Silverstar Zero Eplus					74		0.53				http://www.glastroesch.ch/services/datentabellen-ausschreibungstexte/waermedaemmisolierglas-silverstar/silverstar-e-linie.html (Accessed 27.06.2013)

* Note that the U-value will vary depending on the thickness of the glass, thickness of the cavity, etc. The values in this table are for most cases given for 4-12-4 windows (two panes of 4 mm glass with a 12 mm cavity). However, please check the respective manufacturer sites for more detailed values.

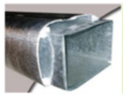
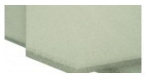
[a] Winter U-value

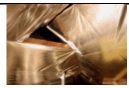
Table A2 Self-applicable films for windows.

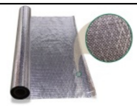
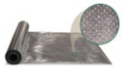
Manufacturer	Product	Illustration	ε	$ε_{aged}$	T_{sol} (%)	T_{vis} (%)	T_{uv} (%)	SHGC	U-value ($W/(m^2K)$)	Additional information
CPFilms Inc. a Subsidiary of Solutia Inc 575 Maryville Centre Drive St. Louis, MO 63141 USA Tel: 1-800-345-6088 Fax: 1-314-674-1950 Vista-films@cpfilms.com www.Vista-films.com	EnerLogic VEP35 SR CDF		0.07		15-19	29-33	1	0.24-0.30	0.34 / 0.30 Winter / summer value	http://www.enerlogicfilm.com/en/ProductPerformance.aspx Measured in accordance with NFRC standards (Accessed 27.06.2013)
	EnerLogic VEP70 SR CDF		0.09		35-46	61-70	1	0.49-0.52	0.34 / 0.31 Winter / summer value	
Classic Window Film 200 Dixon Road Toronto, ON M9P 2L8 Tel: 647-887-5647 Canada classicwindowfilm@gmail.com www.classicwindowfilm.com	Solar window film									http://www.classicwindowfilm.com/film-solar.asp (Accessed 27.06.2013)
Saint-Gobain Performance Plastics Ball Mill Top Business Park, Grimley, Worcestershire, WR2 6LS, UK Tel: +44 (0)1905-640400 Fax: +44 (0)1905 640500 solargarduk@saint-gobain.com http://solargard.com	Ecolux 70		0.09		43	68	< 1	0.48	0.61 Winter value	ASTM and ASHRAE standards http://solargard.com/window-films/commercial/solar-control-films/low-emissivity/ecolux (Accessed 13.11.2013)
	Silver AG 50		0.37		35	51	< 1	0.43	0.78 Winter value	ASTM and ASHRAE standards http://solargard.com/window-films/commercial/solar-control-films/low-emissivity/silver-ag (Accessed 13.11.2013)
	Silver AG 25		0.33		14	22	< 1	0.23	0.75 Winter value	
Hanita Coatings Kibbutz Hanita 22885, Israel	Silver 20 Low-E		0.39		12	17	1	0.20		http://www.hanitaenergy.com/interior-reflective-films (Accessed 27.06.2013)

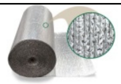
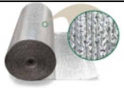
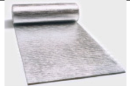
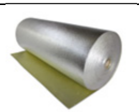
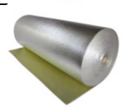
Manufacturer	Product	Illustration	ε	$ε_{aged}$	T_{sol} (%)	T_{vis} (%)	T_{uv} (%)	SHGC	U-value (W/(m^{2}K))	Additional information
Tel: +972 4 985 9919 Fax: +972 4 985 9920 hanita@hanitacoatings.com www.hanitacoatings.com	Silver 35 Low-E		0.45		19	27	1	0.28		http://www.hanitaenergy.com/interior-reflective-films (Accessed 27.06.2013)
3M Tel: +1-866-499-8857 http://solutions.3m.com	Amber 35 Low E Sun Control Window Film		0.34		25	31	1	0.31	0.40	Film attached to a single glass pane http://solutions.3m.com/wps/portal/3M/en_US/Window_Film/Solutions/Markets-Products/Commercial/Sun_Control_Window_Films/Traditional_Series/ (Accessed 27.06.2013)

Table A3 Foils/reflective insulation.

Manufacturer	Product	Illustration	ε	ε_{aged}	Thickness (mm)	Materials	Additional information
Environmentally Safe Products, Inc. 313 W. Golden Ln. New Oxford, PA 17350 USA Tel: 717-624-3581 Fax:717-624-7089 sales@low-e.com www.low-e.com	ESP LOW-E Insulation		0.03			Polyethylene foam core with scrim reinforced double sided aluminium facings	http://www.low-e.com/products/products_view.php?Product=Low-E (Accessed 19.06.2013)
	Econo-E		0.03				http://www.low-e.com/products/products_view.php?Product=Econo-E (Accessed 19.06.2013)
	Attic Floor Insulation		0.03			Double -sided perforated aluminium laminated to polyethylene foam	http://www.low-e.com/products/products_view.php?Product=Attic%20Floor%20Insulation (Accessed 19.06.2013)
	LOW-E HVAC		0.03			Polyethylene foam faced with aluminium on both sides	http://www.low-e.com/products/products_view.php?Product=Low-E%20HVAC (Accessed 19.06.2013)
	SlabShield					Closed cell polyethylene foam applied to both sides of aluminium reflective layer	http://www.low-e.com/products/products_view.php?Product=SlabShield (Accessed 19.06.2013)
	LOW-E Tab		0.03				http://www.low-e.com/products/products_view.php?Product=Low-E%20Tab (Accessed 19.06.2013)
LOW-E UK Ltd Unit 48 Weaver Industrial Estate Blackburne Street Liverpool United Kingdom L19 8JA Tel: 0151 494 9994 Fax: 0560 310 7699 info@low-e.co.uk www.low-e.co.uk	EPS LOW-E Slab shield				11	Foam Facing/ Foil Core/Foam Facing	http://www.low-e.co.uk/low-e-reflective-products?q=Low-E_Insulation_Slab_Shield (Accessed 19.06.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	Thickness (mm)	Materials	Additional information
Sigma Technologies Int'l, LLC 10960 North Stallard Place Tucson AZ, 85737 USA Tel: +1 (520) 575-8013 Fax: +1 (520) 844-1056 info@sigmalabs.com www.sigmalabs.com	irWRAP						http://www.sigmalabs.com/permeable-membranes-const/ (Accessed 19.06.2013)
	3100 Series Radiant Barrier		0.05				http://www.sigmalabs.com/3100-series-rb-overview/ (Accessed 04.12.2013)
Fi-Foil Company, Inc. 612 Bridgers Ave. W., PO Box 800 Auburndale, Fl 33823 USA Tel: +1-800-448-3401 www.fifoil.com	Silver shield radiant barrier		0.03			Metalized polyvinyl chloride film with aluminium, kraft paper reinforced with tri-directional fibreglass.	http://www.fifoil.com/Builders/Products/ProductInfo/?ID=3 (Accessed 19.06.2013)
	FSK shield					Aluminium foil bonded to kraft paper reinforced with tri-directional fibreglass	http://www.fifoil.com/Builders/Products/ProductInfo/?ID=4 (Accessed 19.06.2013)
	Radiant shield		0.03		0.012 inch	Woven polyethylene sandwiched between two aluminium surfaces.	http://www.fifoil.com/Builders/Products/ProductInfo/?ID=5 (Accessed 19.06.2013)
Glidevale Limited 2 Brooklands Road Sale Cheshire M33 3SS UK Tel: 0161 905 5700 Fax: 0161 905 2085 info@glidevale.com www.glidevale.com	Protect VC foil ultra						http://www.glidevale.com/protect_vc_foil_ultra.html (Accessed 19.06.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	Thickness (mm)	Materials	Additional information
Carolina Energy Conservation 100 Lichen Court, Unit A Myrtle Beach, SC 29588 USA Tel: +1 (843) 748 0295 (843) 748 0583 info@carolinaenergyconservation.com www.carolinaenergyconservation.com	ECO-Guard PLUS reflective insulation						http://www.carolinaenergyconservation.com/eco-guard-plus-reflective-insulation.html (Accessed 20.06.2013)
Energy Efficient Solutions LLC 1126 S Cedar Ridge Dr. Suite 122 Duncanville, TX 75137-302 USA Tel: +1 972.283.0163 Fax: +1 972.852.3151 sales@energyefficientsolutions.com www.energyefficientsolutions.com	ARMA foil		0.05		4		http://www.energyefficientsolutions.com/ARMAFOIL.asp (Accessed 20.06.2013)
	ARMA foil VB		0.05		4		http://www.energyefficientsolutions.com/ARMAFOIL-VB.asp (Accessed 20.06.2013)
INNOVATIVE INSULATION, INC. 6200 W. Pioneer Pkwy. Arlington, TX 76013 USA Tel: (817) 446-6200 Fax: (817) 446-6222 www.radiantbarrier.com	Super R Diamond		0.05			Two sided reflecting metalized film with polyester scrim reinforcement	http://www.radiantbarrier.com/diamond-insulation.htm (Accessed 02.09.2013)
	Super R Platinum		0.05			Two-sided reflecting metalized film with a cross-laminated polyolefin reinforcement	http://www.radiantbarrier.com/platinum-insulation.html (Accessed 02.09.2013)
	Super R Plus		0.05			Two-sided reflecting metalized film with polyethylene reinforcement	http://www.radiantbarrier.com/plus-insulation.htm (Accessed 02.09.2013)

Manufacturer	Product	Illustration	ε	ε_{aged}	Thickness (mm)	Materials	Additional information
	Tempshield single bubble		0.05		1/8 inch	One layer of barrier bubble film laminated between to layers of reflective metalized film	http://www.radiantbarrier.com/bubble-foil-insulation.htm
	Tempshield double bubble		0.05		1/8 inch	Two layers of barrier bubble film laminated between to layers of reflective metalized film	http://www.radiantbarrier.com/double-bubble-insulation.htm (Accessed 02.09.2013)
SA.M.E. S.r.l. Via Ferriera, 68 06089 Torgiano (PG) Italy Tel: +39 - 075 599 65 28 Fax: +39 - 075 597 68 46 info@samesrl.com www.same-foil.com	Isoliving		0.06		8	Tow layers of bubble polyethylene and two layers of low-e aluminium film	http://www.same-foil.com/public/pdfprodotti/9.pdf (Accessed 02.09.2013)
DuPont www.dupont.com/	Airguard Reflective		0.05		0.43	A composite of polypropylene, polyethylene and an aluminium foil	http://www2.dupont.com/Tyvek_Construction/en_IE/products/dry_lining/airguard_reflective.html (Accessed 02.09.2013)
Polyair 4 Macdonald Road, Ingleburn, NSW 2565, Australia Tel: +61 2 9829 2299 Fax: +61 2 9829 2211 sales@polyairinsulation.net.au www.reflectiveinsulation.com.au	Polyair Performa 4.0		0.03		4	Core of fire retardant closed cell foam, two external layers of aluminium foils	http://www.reflectiveinsulation.com.au/polyair_performa_4.html (Accessed 02.09.2013)
	Polyair Performa 7.0		0.03		7	Core of fire retardant closed cell foam, two external layers of aluminium foils	http://www.reflectiveinsulation.com.au/polyair_performa_7.html (Accessed 02.09.2013)
Reflectix #1 School Street, P.O. Box 108, Markleville, IN 46056 Tel: (765) 533-4332 Fax: (765) 533-2327 customerservice@reflectixinc.com www.reflectixinc.com	Double reflective insulation		0.06		5/16 inch	Two reflective layers of film bonded to two internal layers of heavy gauge polyethylene bubbles	http://www.reflectixinc.com/basepage.asp?Page=Double+Reflective+Insulation&pageIndex=622 (Accessed 02.09.2013)
	Single reflective insulation		0.06		5/16	One reflective layer of film bonded to two internal layers of heavy gauge polyethylene bubbles	http://www.reflectixinc.com/basepage.asp?Page=Single+Reflective+Insulation&pageIndex=755 (Accessed 02.09.2013)
	Concrete slab insulation				5/16 inch	Aluminium bonded to an external layer of polyethylene and internally bonded to two layers of heavy gauge polyethylene bubbles	http://www.reflectixinc.com/basepage.asp?Page=Concrete+Slab+Insulation&pageIndex=618 (Accessed 02.09.2013)

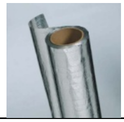
Manufacturer	Product	Illustration	ε	ε_{aged}	Thickness (mm)	Materials	Additional information
	Radiant barrier		0.05			Two reflective layers of film bonded together enclosing a heavy gauge poly scrim	http://www.reflectixinc.com/basepage.asp?Page=Radiant+Barrier&pageIndex=624 (Accessed 02.09.2013)

Table A4 Opaque spray and brush paints.

Manufacturer	Product	Illustration	ε	Binder	Solvent	VOC (g/L)	Shelf life	Additional information
SOLEC-Solar Energy Corp. 129 Walters Ave. Ewing, NJ 08638-1829, USA Tel: +1 609-883-7700 Fax: +1 609-883-5489 info@solec.org www.solec.org	LO/MIT-I		0.21-0.37 Depends on surface it is applied too	Silicone	Xylene	664.41	Best if used 1 year from date of manufacture	http://www.solec.org/lomit-radiant-barrier-coating/lomit-technical-specifications/ Conform to ASTM standard C1321-98 (Accessed 19.06.2013)
	LO/MIT-II		0.21-0.37 Depends on surface it is applied too	Silicone emulsion	DI Water	172.73	Best if used 6 months from date of manufacture	
	LO/MIT-II MAX		0.15-0.17 Depends on surface it is applied too	Silicone emulsion	DI Water	215.48	Best if used 1 year from date of manufacture	
	SOLKOTE		0.20-0.49 depending on layer thickness and surface	Silicone polymer	Xylene	812	Best if used 1 year from date of manufacture	http://www.solec.org/solkote-selective-solar-coating/solkote-technical-specifications/ (Accessed 19.06.2013)
STS Coatings, Inc. 347 Hwy 289 Comfort, TX 78013 USA Tel: +1 830-995-5177 Fax: +1 830-995-5705 www.stscoatings.com	HeatBloc-Ultra		0.19			< 50	6 months	Interior use only http://heatbloc.net/heatblocultra.html (Accessed 20.06.2013)

Manufacturer	Product	Illustration	ε	Binder	Solvent	VOC (g/L)	Shelf life	Additional information
Carolina Energy Conservation 100 Lichen Court, Unit A Myrtle Beach, SC 29588 USA Tel: +1 (843) 748 0295 (843) 748 0583 info@carolinaenergyconservation.com www.carolinaenergyconservation.com	ECO-Guard coating		0.15-0.24					http://www.carolinaenergyconservation.com/lo-mit.html (Accessed 20.06.2013)
BASF Corporation/Chemrex USA Tel: +1 973 245-6000 www.basf.com	RADIANCE e-0.25		0.23			212	1 year	http://www.buildingsystems.basf.com/p02/USWeb-Internet/buildingsystems/en_GB/content/microsites/buildingsystems/products/items/Radiance_e-0.25_Attic_Barrier (Accessed 20.06.2013)
Henry Company 999 North Sepulveda Blvd., Suite 800 El Segundo, CA 90245 USA Tel: +1 800-486-1278 productsupport@henry.com http://henry.com	LiquidFoil		0.16			185		http://henry.com/roofing/coolroofcoatings/liquidfoil (Accessed 20.06.2013)